Memo

To:	CCB
From:	X. Yang, K. McLaughlin, I. Bondár, J. Bhattacharyya, H. Israelsson
Date:	December 27, 2001
Subject:	Pn & Sn SSSCs in Europe, North Africa, Middle East, and Western Asia
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Abstract

We recommend a new set of regional Source Specific Station Corrections (SSSCs) be implemented in the CMR baseline processing configuration. The proposed Pn and Sn SSSCs are expected to improve locations in Europe, the Mediterranean, North Africa, Middle East, and Western Eurasia due to more accurate (calibrated) regional travel-times and reduced model errors. Dependencies and risks are limited. Online and offline tests were conducted. Online tests verified the stability of the proposed changes in the operational environment. Offline tests validated the model-based corrections and verified improvements can be expected with current and future IMS networks. The SSSCs can be installed with minimal time and resources.

This proposal reflects Phase 1 results of a three-year project to calibrate shallow focus (depth < 40 km) regional Pn and Sn travel times for IMS stations in Europe, North Africa, the Middle East and Western Asia by the Group-2 Location Calibration Consortium (SAIC, Colorado University Boulder, Harvard University, Multimax, Geophysical Institute of Israel, University of California San Diego, and Western Services). A 3-D crust and upper-mantle seismic-velocity global model was constructed by inverting group and phase velocity data sets, and SSSCs were obtained from the 3D model by ray tracing. Since the current IDC software cannot handle depth-dependent SSSCs and it applies SSSCs at all source depths in locating events, in Phase 1 we developed Pn and Sn SSSCs for a source depth of 10 km as a compromise for all regions of crustal seismicity. Modeling errors were estimated from travel-time residuals. Model validation was performed by comparing the 3D model-based path corrections with empirical path corrections from an analysis of events clusters and by relocation of GT reference events. Relocation test results of about 600 GT0-GT10 events (96% of them are GT0-GT5) in the study region met the evaluation criteria recommended by the Working Group B in 1999. Mislocations are improved for the majority of events, and error ellipses are significantly reduced without loss of coverage. Online testing on the DTRA CMR R&D Testbed showed no significant impact of SSSCs on automatic or interactive system performance. Further regional SSSC refinements are expected in February 2003 as part of a Phase 2 effort that will include Pg, Lg, and possibly depth dependent regional P and Pn.

Statement of Objective

The objective of this proposal is to install validated regional ($\Delta \leq 20°$) phase (Pn & Sn only) shallow focus (depth < 40 km) SSSCs in the CMR baseline processing configuration to improve seismic event locations in Europe, North Africa, the Middle East, and Western Eurasia. Improvements include reduction in location bias (mislocation) and reduction of 90% confidence ellipses without loss of 90% coverage.

Summary of Proposed Changes

We propose two changes:

1. Install model-based Pn and Sn SSSCs (GA & ARS environments) for 63 IMS stations (currently data for 26 of the stations are available in CMR processing) in Europe, North Africa, the Middle East, and Western Eurasia (Table 1; Figures 1-2). This will replace existing Pn and Sn SSSCs for six Fennoscandian IMS stations based on 1D models (Yang and McLaughlin, 1999) with a set of 3D model-based SSSCs consistent with new 3D model-based SSSCs for the rest of Europe.
2. Enable use of SSSCs in the automated GA processing environment consistent with Patch 7.0.193 on the existing Testbed.

Appendix 1 summarizes the development, validation, and testing of the model-based SSSCs. Details are provided in a number of documentations (Appendices 2-9) that are available at http://g2calibration.cmr.gov/calibration/result.html. The 1999 Oslo recommendations for seismic event location are also included as a reference (Appendix 10).

Expected Benefits

Installing Pn and Sn SSSCs will improve locations in Europe, the Mediterranean, North Africa, Middle East, and Western Eurasia due to more accurate (calibrated) regional travel-times and model errors.

- About 50% reduction of Pn and Sn a-priori travel time variances will result in smaller confidence ellipses. (Tests 1-11)
- Calibrated regional travel times will reduce location bias due to incorrect (uncalibrated) regional travel times. (Tests 2-11)
- Conservative selection of model errors will still maintain 90% coverage for low ndef events with regional phases. (Tests 2-11)
- Calibrated model errors will result in improved relative weighting of regional and teleseismic phases. (Tests 10-11)
- Calibrated regional travel times will result in more useful Pn and Sn phases. (Test 5)

Possible Risks and Dependencies

Dependencies are limited. The only applications affected are those that call libloc and locate events with regional phases using SSSCs: GA and ARS. The proposed changes affect only the following events:

- Shallow focused events with depths less than 40 km (Pn & Sn are undefined deeper than 40 km)
- Events in Europe, North Africa, the Middle East, and Western Asia
- Events located with Pn & Sn. Events with a large numbers of teleseismic rather than regional phases are only weakly affected. Events located with only teleseismic (>20 degrees) phases are unaffected.

Risks are small or can be mitigated:

- GA & ARS computational load and memory requirements. The proposed Pn and Sn SSSCs will add only moderate memory requirements and computational costs. Online testing shows that no significant impact is expected on the current system & computer capacities. A significant number of future IMS stations are not currently operational. If problems with memory or process slow downs are observed, the corrections could be removed easily. We expect GA will meet the requirements for robust real time processing even with a fully operational IMS network running regional SSSCs.
- Mixing uncalibrated data with calibrated data. Ideally we would limit mixing uncalibrated & uncalibrated data in event location. Pg and Lg SSSCs are not proposed at this time. Pg & Lg SSSCs at Fennoscandian stations will remain in the system. No teleseismic SSSCs exist or are proposed. Offline testing demonstrated that mixing uncalibrated data with calibrated data diluted improvements and did no harm compared to using all uncalibrated phases (IASPEI91).
- Large non-Gaussian measurement errors (outliers) will continue to result in larger than predicted mislocations for a small percentage of events (~3-5%). A recent study by Yang et al. (2001b) has shown existing error models (Gaussian model and measurement errors) are sufficient to predict 90% confidence bounds but in order to predict 95%-97% confidence bound, standard errors would have to be drastically inflated and median (50%) and 90% confidence regions would be excessively large. This problem exists for both teleseismic & regional phases and is beyond the scope of the proposed regional calibrations. A conservative compromise was required to select conservative model errors that overestimate the median confidence bounds, correctly predict 90% coverage, but will inevitably under predict the 95%-97% coverage.

Summary of Testing

The scientific justifications of the Pn and Sn SSSCs and their model errors are described in Appendix 1. Details on SSSC testing, data, test results are given in Appendices 5-9. All appendices are available at http://g2calibration.cmr.gov/calibration/result.html.

In this section, we briefly summarize the key offline and online tests. Online tests verified the stability of the proposed changes in the operational environment. Offline tests validated the model-based corrections and verified improvements can be expected with current and future IMS networks. The testing generally followed the Group 2 "Phase 1 Validation Test Plan - March 2001" (http://g2calibration.cmr.gov/calibration/files/g2testplan.pdf) coordinated with the CMR R&D Testbed in March 2001.

Online Test Summary

Objective: Ensure SSSCs will not have negative impact on automatic or interactive processing.

Description: Online testing of Automatic (Global Association, GA) and Interactive (Analyst Review Station, ARS) processing were conducted on the DTRA CMR R&D Testbed in July of 2001. Table 1 and Figure 1 show the 63 IMS stations with Pn and Sn SSSCs tested. Test details are described in Appendix 5.

Results: All tests were successful. Test results showed no significant impact on the system when SSSCs were turned on in both automatic and interactive systems for the 63 IMS stations in the study region as well as the existing 1D SSSCs in Fennoscandia (Pg and Lg) and North America (Pn, Sn, Pg, and Lg).

SSSCs were first introduced into PIDC REB analysis using ARS in 1999, but so far no SSSCs have been applied to the automatic system in the PIDC/IDC systems. Since last year a CMR RDSS evaluation has been conducted, and a CCB proposal on applying SSSCs to GA is currently under consideration (Bondár, 2001). Application of existing SSSCs (Fennoscandia, North America) in the automatic processing system was installed on the Testbed as Patch 7.0.193 in October 2001. Comparisons of GA performance with and without current SSSCs showed no significant increase in memory usage and only marginal increases (~1-3%) in CPU time. Total processing time increased by ~10%.

Offline Test Summary

Event relocation testing for the Group-2 region was conducted to verify location improvements on both accuracy and uncertainty. Events used in testing are primarily GT0-GT5 events, but GT10 events may also be used to extend the region coverage where GT0-GT5 events are not available. The events included in testing were not involved in constructing the 3D seismic velocity model. Events in four data sets were relocated, with and without SSSCs:

- Data Set 1: 425 Fennoscandian GT events used in a previous study (Yang and McLaughlin, 1999) for benchmark testing with existing 1D SSSCs in Fennoscandia
- Data Set 2: 571 High-quality GT0-GT10 events in the Group-2 Reference Event List 1.1 for thorough validation testing (only 24 of the events are GT10)
- Data Set 3: 15 GT10 Mid-Ocean Ridge and Transform (MORT) events for extended coverage into the ocean basins
- Data Set 4: 6853 GSETT-3 REB events for real world test

Several offline validation tests and investigations were conducted to test and validate both 3D model-based travel times and their new model errors. The tests can be separated into two categories. The first category serves to validate model-based calibrations and their model errors by either direct comparison to data or by relocation. The second set of tests serves to validate expected improvements in either existing or future IMS systems and ensure that the corrections will “do no harm” by relocation.

The first category of offline “model validation” and tests includes:

1. Comparison with JHD empirical path corrections,
2. Relocation of 571 GT0-GT10 reference events,
3. Relocation of 150 GT5-GT10 reference events by grid search and L1 norm,
4. Relocation of 15 GT10 MORT reference events,
5. Relocation of 6835 GSETT-3 REB events.

While the above tests strongly argue the new calibrated regional travel times are superior to IASPEI91, they are insufficient to guarantee installation will result in operational improvements for either the existing or future IMS/IDC network locations. The following offline tests (the second category) were conducted to test and validate “expected benefits” or at least ensure the proposed calibrations will “do no harm”:

6. Relocation of 425 Fennoscandian GT events,
7. Relocation of 240 GT0-GT10 reference events using IMS stations and regional phases,
8. Relocation of 318 GT0-GT10 reference events using IMS+surrogate stations and regional phases,
9. Relocation of 246 (&340) GT0-GT10 reference events using IMS stations only (& IMS+surrogate stations) and mixed calibrated & uncalibrated Pn & Sn phases,
10. Relocation of 245 (&328) GT0-GT10 reference events using IMS stations only (& IMS+surrogate stations) and mixed calibrated Pn &Sn and uncalibrated Pg, Lg, and teleseismic phases,
11. Relocation of 59 (& 85) small GT0-GT10 reference events using IMS stations only (& IMS+surrogate stations) and calibrated Pn &Sn and uncalibrated Pg, Lg, and teleseismic phases.

IMS surrogate stations are used to simulate the IMS network where future IMS stations are not yet deployed and/or data are not available from existing IMS stations for testing. They are existing stations within 75 km of the corresponding IMS stations. Events used in relocation tests 7-11 are subsets of the data set in Test 2 (Data Set 2). Mixing calibrated and uncalibrated data in event location is assessed in the category 2 testing. Table 2 summarizes the differences between the 10 relocation tests as well as the test data sets.

To assess location improvement using SSSCs, relocation results with SSSCs are compared with those without SSSCs based on a set of evaluation metrics. The metrics include those recommended by the 1999 Oslo Location Workshop (CTBT/WGB/TL-2/18, 1999). Additional metrics were also developed to measure the performance of the SSSCs that take into account the total error model. All available events that are locatable were included in each test evaluation; no events were discarded based on any event outlier rejection.

TEST 1. Comparison with JHD empirical path corrections

Objective: Test validity of model-based corrections and their model errors.

Description: About 4,000 P-phase empirical cluster-station path corrections at regional distances were estimated with JHD (Joint Hypocenter Determination) for 47 event clusters in Europe, Middle East and North Africa. Uncertainties were estimated for each empirical cluster-station path correction. JHD & SSSC path correction pairs were then compared individually, by cluster, and by distance.

Results:

- Model-based path corrections (SSSCs) and model errors show encouraging agreement with empirical JHD path corrections.
- Statistical tests (Pearson test) indicate significant correlation for 37 clusters. Correlation values were generally higher for paths longer than 5°, and clusters with many short paths showed low correlation. The correlations are consistent with the model errors.
- The overall improvement provided by the CUB1.0 SSSCs relative to IASPEI91 was demonstrated by a 30% reduction in the bulk standard deviation for all clusters; the 1.53 sec standard deviation for JHD-IASPEI91 corrections dropped to 1.15 sec for the JHD-SSSC differences (44% variance reduction). The JHD-SSSC differences are approximately Gaussian.
- Comparisons between the JHD corrections and the CUB 1.0 model errors (SSSCs) with associated uncertainties indicated that the a-priori CUB 1.0 model errors (SSSCs) might be on the conservative side.
- The empirical path corrections as a function of distance, both among cluster pairs and station pairs, show high correlations for distances up to 1° supporting validity of the 1° sampling of SSSCs.

More detailed results are summarized in Appendix 1. The full documentation of this work is given in Appendix 7.

TEST 2. Relocation of 571 GT0-GT10 reference events (Data Set 2)

Objective: Test validity of model-based corrections and their model errors

Description: The test data set includes 571 GT0-GT10 crustal events from the Group-2 Consortium Reference Event List 1.1 with at least 3 Pn (Sn) defining phases (Figure 3). Data are available for 33 out of 63 IMS stations in the Group-2 region (Table 1); many other IMS stations are in areas with ray path coverage in this data set. Events are mostly GT0-GT10 except 24 GT10 events included in this data set to extend the coverage of the region. Events were relocated using only Pn and Sn phases, with and without SSSCs, at all available stations. Depth is fixed to zero since the events are mostly shallow (85% of the events with depths < 10 km). Comparisons are made between relocations with and without SSSCs for evaluation of location improvement using SSSCs.

Results:

- More events were improved than deteriorated and improvements were generally larger than deteriorations. 60% of 571 events improved with a median mislocation reduction of 7.9 km (Figures 4-5) compared to the median mislocation increase of 6.4 km. 63% of 57 GT0 locations improved. 58% of 57 GT0 events improved more than 20% compared to only 28% of 57 GT0 events deteriorated by more than 20%. Of the full reference event population of 571 events, 47% were improved by more than 20% compared to only 31% deteriorated by more than 20%. 46% more (41 vs. 28) events were located within GTX accuracy. 34 events moved from outside to inside GTX accuracy compared to 21 events that moved from inside to outside GT accuracy. 14% more (361 vs. 317) events located were within 18 km using regional phases alone.
- The entire mislocation distribution was reduced by statistically significant amounts (Figure 5). The median mislocation was reduced by only 14% (from 16.5 to 14.1 km) but at a 95% significance level. The 80th percentile mislocation decreased 33% (from 43 km to 29 km).
- When GT location uncertainties, measurement errors, and model errors are actually taken into account, it was found that degradation is less than expected by random chance more than 80% of the time. Small mislocations (either small w.r.t. GT location uncertainty or small w.r.t. the estimated error ellipse) generally remained small while larger more important mislocations were generally reduced (McLaughlin and Bondár, 2001).
- All events have reduced “honest” error ellipses due to reduced model errors without losing 90% coverage (Figure 6). The median ellipse area was reduced 51% (from 4600 to 2240 km^2). Coverage was closer to the theoretical χ^2 distribution for the 20th, 50th, 80th and 90th percentiles indicating a better fit to the overall error distribution. 74 more events (increase from 11% to 24%) satisfied the “trinity criteria” (ellipse area <1000 km^2, coverage of GT, and absolute mislocation < 25 km) using regional phases alone. The reduced error “honest” ellipses are only possible with the calibrated travel times.
- Origin time errors were reduced for 99% of the events with median improvement 0.9 seconds (29% improvement), from 3.1 to 2.2 sec. This indicates the proposed regional calibrations are less biased and contain less baseline (static) errors.
- The “normalized” standard error of observations improved for 61% of events with a median 17% variance reduction. While variance reduction is not often a good indicator of performance, when it is observed along with reduced bias (epicenters and origin times), it is an indicator of a superior model.
- The calibrations met or exceeded evaluation criteria recommended by the 1999 Oslo Location Workshop (CTBT/WGB/TL-2/18, 1999). The median mislocation is significantly improved and median area of error ellipses is significantly reduced without loss of 90% coverage.

Test details are described in Appendix 1 and the full documentation is given in Appendix 8.

TEST 3. Relocation of 150 GT1-GT5 reference events by grid search and L1 norm (Data Set 2)

Objective: Test validity of model-based corrections.

Description: An independent relocation test was conducted by the University of Colorado at Boulder (UCB) using an L1 norm grid search method. A total of 150 events from 15 event clusters obtained from a set of cluster analyses (a subset of the test data set described above) were relocated using Pn phases only with the CUB 1.0 Model compared to 1-D AK135 model (regional travel times are the same between AK135 and IASPEI91).

Results:

- Relocation model validation results are generally consistent with tests using EvLoc and do not depend upon the very specific choice of L1 norm vs. L2 norm (EvLoc) and grid search vs. linearized least squares iteration (EvLoc).
- Test results demonstrate improvement in event location using SSSCs as a strong function of ndef (number of defining phases) and outlier rejection criteria. Low ndef events are very strongly influenced by outliers and therefore low ndef events have a large inherent scatter and limited resolving power to test and validate models.
- When ndef >15, mislocations are improved for 75% of the events with average mislocation reduced from 19 km to 11 km.

Test details are described in Appendix 1 and the full documentation is given in Appendix 9.

TEST 4. Relocation of 15 GT10 MORT reference events (Data Set 3)

Objective: Test model-based corrections and model errors in regions not covered by GT0-GT5 reference events.

Description: To extend path coverage into the ocean basins we test using available MORT GT10 events. GT0-GT5 events are not available in the ocean basins and only these less well defined GT10 reference events are available. The test revealed the strong location sensitivity to outliers between 15° to 20° due to misassociations of P to Pn. Only regional P phases beyond 15 degrees could be associated, and 15 MORT events can be relocated with Pn arrivals under 15°.

Results:

- 80% of the events improved by a median 21 km, compared to 20% of the events which deteriorated by a median 11 km.
- The percentage of events that failed the 90% coverage test was within what could be expected based on the sample size.
- Relocations appear to be better correlated with the ridges and transforms.

Test details are described in Appendix 1 and the full documentation is given in Appendix 8.

TEST 5. Relocation of 6835 GSETT-3 REB events (Data Set 4)

Objective: Test the effect of calibration in real world situation.

Description: The data set includes 6835 GSETT3 REB events between 01/01/1995 and 02/20/2000 with shallow depth (< 40km) and at least 3 Pn (Sn) phases. Events were relocated using only Pn and Sn phases, with and without SSSCs. Different from other offline relocation tests, in this test slowness and azimuths were also used, with SASCs (Slowness Azimuth Station Corrections), if they were defining in the REB. About 1/3 of the defining phases in the data set are azimuth defining (40% of these with regional SASCs) but almost none are slowness defining. A statistical test was conducted to test the hypothesis that seismicity would be more clustered with calibrations.

Results:

- More events were relocated with than without SSSCs, indicating that the better travel time and error predictions facilitate more consistent location estimates. 899 events located only with SSSCs but not without, and 270 events located only without SSSCs but not with. Note that, unlike the REB which uses all phases, in the relocation test only Pn and Sn phases were used. 4786 events located both with and without SSSCs; the median distance between the two sets of locations is 0.08 km, with smad (median of absolute deviation normalized to a Gaussian distribution) of 0.07 km.
- Event clusters become tighter with SSSCs. For events within 5 km of other events, the median nearest neighbor distance decreased from 1.53 km to 1.47 km. While the changes are small, the reduction is statistically significant.

Test details are described in Appendix 1 and the full documentation is given in Bondár and McLaughin (2001).

TEST 6. Relocation of 425 Fennoscandian GT events (Data Set 1)

Objectives:

- Test replacement of existing Fennoscandian 1D model-based SSSCs with 3D model-based SSSCs consistent with the rest of Europe.
- Validate 3D model by comparison with accepted 1D models in well studied Fennoscandia.

Description: The benchmark test were conducted to relocate the GT events previously used to test Fennoscandian 1D model-based SSSCs (Yang and McLaughlin, 1999). Direct comparisons of the two sets of SSSCs were also made.

Results:

- The new 3D model-based calibrations perform as well or better than the existing 1D model-based calibrations in Fennoscandia, North/Central Europe, and in the Mid-Atlantic.

- Direct comparison of SSSCs indicate that there should be no impact in replacing the existing SSSCs with 3D SSSCs in Fennoscandia. The average Pn misfit between the two sets of SSSCs is -0.25 sec (CUB model is faster). 84% and 100% of the Pn differences are below the 1σ and 2σ levels, respectively, where σ is the CUB modeling error.

Test details are described in Appendix 1 and the full documentation is given in Appendix 8.

<u>TEST 7. Relocation of 240 GT0-GT10 reference events using IMS stations only and regional phases (Data Set 2)</u>

Objective: Test relocation performance with the “current” sparse IMS network

Description: A total of 240 GT0-GT10 events were relocated using only IMS stations to simulate regional location with calibrated Pn and Sn phases in an IMS network.

Results:

- Calibration does more good than no-calibration and calibration “does no harm”. 49% of 240 events are improved by more than 20%, compared to 31% of the events deteriorated by 20% or more. The mislocation distribution for this test set is not distinguishable from the larger set in Test 2.
- Test results demonstrate SSSCs should improve locations based on regional data for a sparse IMS network.

Test details are described in Appendix 1 and the full documentation is given in Appendix 8.

<u>TEST 8. Relocation of 318 GT0-GT5 reference events using IMS+surrogate stations and regional phases (Data Set 2)</u>

Objective: Test relocation performance with the future sparse IMS network.

Description: A total of 318 reference events were relocated using only IMS+surrogate stations to simulate regional location with calibrated Pn and Sn phases in a sparse future IMS network.

Results:

- Calibration results in improvement. 59% of the events improved by a median 8.2 km and 41% of the events deteriorated by a median 6.2 km.
- Test results demonstrate SSSCs should improve locations based on regional data for a fuller sparse IMS network.

Test details are described in Appendix 1 and the full documentation is given in Appendix 8.

<u>TEST 9. Relocation of 246 (& 340) GT0-GT10 reference events using IMS stations only (& IMS+surrogate stations) and mixed calibrated & uncalibrated Pn & Sn phases (Data Set 2)</u>

Objective: Test if mixing calibrated and uncalibrated regional phases will cause harm in an operational sparse IMS network.

Description: Tests were conducted for IMS stations only & IMS+surrogate stations, respectively, with calibrated Pn and Sn phases (Group 2) combined with uncalibrated Pn and Sn phases (Group 1 and others) in a simulated IMS network. Relocation results are compared with those without SSSCs for each of the two tests.

Results:

- Calibration improvements are generally diluted. In both cases the majority of events are improved by a median 5-6 km, compared to a median deterioration of 4-5 km. Error ellipse area is reduced by about 40% within the 90% coverage.
- The results indicate that mixing calibrated and uncalibrated regional phases in the IMS network does no harm.

Test details are described in Appendix 1 and the full documentation is given in Appendix 8.

<u>TEST 10. Relocation of 245 (& 328) GT0-GT10 reference events using IMS stations only (& MS+surrogate stations) and mixed calibrated Pn &Sn and uncalibrated Pg, Lg, and teleseismic phases (Data Set 2)</u>

Objective: Test if mixing calibrated regional with uncalibrated regional and teleseismic phases will cause harm in an operational sparse IMS network.

Description: Tests were conducted with calibrated Pn and Sn phases combined with uncalibrated Pg, Lg, and teleseismic phases using only IMS and IMS+surrogate stations. This simulate the IMS network with the Phase 1 Pn & Sn SSSCs installed in the system.

Results: Calibrations “do no harm” in event location when mixed with uncalibrated regional (Pg & Lg) and teleseismic phases in a simulated IMS network.

Test details are described in Appendix 1 and the full documentation is given in Appendix 8.

<u>TEST 11. Relocation of 59 (& 85) small GT0-GT10 reference events using IMS stations only (& IMS+surrogate stations) and calibrated Pn &Sn and uncalibrated Pg, Lg, and teleseismic phases (Data Set 2)</u>

Objective: Simulate/test relocation performance for small events detected by a sparse IMS network.

Description: Previous test results did not simulate the situation of a small event detected by the sparse IMS network. These small events are generally recorded by regional stations and may not be seen by many teleseismic stations. Since information on magnitude and signal-to-noise ratios are generally unavailable for the reference events used in testing, small events are selected based on the ratio of regional to teleseismic phases. Tests were conducted with a subset of events that more represent small events detected in a sparse IMS network.

Results:

- 67% of small events improved by a median 7.0 km and 33% events deteriorated by a median 1.1 km when the number of teleseismic phases was no more than that of the regional phases.
- When the number of teleseismic phases was increased three-fold, 71% events improved a median 5.0 km and 29% deteriorated a median 2.8 km.
- This simulation argues that Pn and Sn SSSCs will generally improve locations for small events in the sparse IMS network when mixed with uncalibrated regional (Pg & Lg) and teleseismic phases.

Test details are described in Appendix 1 and the full documentation is given in Appendix 7.

Summary of Validation Tests

The above battery of offline and online tests were designed to support the “Expected Benefits” claimed above given the limited available GT reference events, uncertainties in GTX locations, real measurement errors (including misassociations), and projected misfit of the new calibrated travel times w.r.t. the real Earth. In the presence of these uncertainties, it was necessary to conduct tests of the model and model errors using large numbers of reference events to provide statistical significance. Given measurement errors are not zero, model errors are not zero, and GTX location uncertainties are not zero, we should always expect a fraction of test events to deteriorate. In fact, validation of the total error model requires that a certain fraction of test events must deteriorate.

- The model and model errors were validated by comparison with empirical cluster-station path corrections and their associated statistics. (Test 1)
- The model and model errors were validated by relocation tests using only calibrated Pn & Sn phases. Error ellipses were reduced 50% without loss of 90% coverage. Relocations show statistically significant event location improvement. The calibrations met or exceeded evaluation criteria recommended by the 1999 Oslo Location Workshop (CTBT/WGB/TL-2/18, 1999). Given measurement and model errors, deterioration was less than expected by pure random chance for over 80% of the test events. (Tests 2, 3, 4, and 6)
- Given the validated calibration model and conservative model errors, relocation tests with IMS and IMS surrogate stations further demonstrated event locations will most likely be improved for the current and future IMS network. (Tests 7, 8, 9, 10, and 11)
- Relocation tests simulated current and future IMS networks with calibrated Pn and Sn (Group 2) and uncalibrated Pn & Sn phases (Group 1) and found diluted improvements but in general the mixture of calibrated and uncalibrated phases “does no harm”. (Test 9)
- Relocation tests simulated current and future IMS networks operating with mixed calibrated Pn & Sn phase with uncalibrated Pg & Lg regional phases together with uncalibrated teleseismic and found diluted improvements but in general the mixture of calibrated and uncalibrated phases “does no harm”. (Tests 10 and 11)
- Existing 1D model-based SSSCs in Fennoscandia can safely be replaced with 3D model-based SSSCs consistent with the rest of the proposed calibrations. (Test 6)

- The more than10% increase in GSETT-3 REB events that could be located using regional phases alone, combined with the reduction in model errors, and the reduction in “normalized” standard error of observations argue that regional Pn and Sn phases become more useful with the proposed SSSCs. (Tests 2 and 5)

Schedule and Plan for Implementation

We recommend to install the Pn and Sn SSSCs for the 63 IMS stations. Files may be obtained from tar files in /net/fox/export/group2/RDTB_delivery/Patch1, Patch1.tar.gz and GA_grid.tar.gz. To install the SSSCs, the specification file, and parameters in par files:

- Delete the existing Pn and Sn SSSC files for Fennoscandian stations (Yang and McLaughlin, 1999), *TT.$sta.$phase.reg.fenno*, where $phase is Pn or Sn. This includes stations ARCES, FINES, HFS, NOA, NRIS, and SPITS.
- Copy the SSSC files, *TT.$sta.$phase.reg.Group2_1*, from the Testbed or Patch1.tar.gz and Update_Fenno_SSSC.tar.gz to directory *$(STATICDIR)/TT/iasp91/SSSC*, where *$(STATICDIR)=$(CMS_CONFIG)/earth_specs* and *$(CMS_CONFIG)=/cmss/config*.
- Copy the specification file, *ars.defs*, from the Testbed or Patch1.tar.gz to directory *$(STATICDIR)/TT/vmsf* to replace the existing *ars.defs* (for ARS) and the contents in *ims.defs* (for GA). If ARS and GA are to share the same file, change the file name specified by parameter $VMSF for one of the two application par files.
- Set *sssc_level=1* in *$AUTOMATIC-DIR/GA/GA.par* where *$AUTOMATIC-DIR=$(CMS_CONFIG)/app_config/automatic*.
- Replace the GA grid files in *$(STATICDIR)*/GA by copying from the Testbed or GA_grid.tar.gz.

Costs and Resources Required for Implementation

The installation should take no more than a man day.

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Table 1: Recommended Pn and Sn SSSCs for 63 IMS stations

treaty #	station name	lat (N)	lon (E)	elev (km)	treaty #	station name	lat (N)	lon (E)	elev (km)
PS11	BGCA	5.1761	18.4242	0.576	AS3*	GNI	40.0530	44.7240	1.460
PS15	DBIC	6.6701	-4.8563	0.025	AS7	CHT	22.4000	91.8000	0.000
PS16	LXAR	26.0000	33.0000	0.000	AS11	RCBR	-5.8000	-35.9000	0.000
PS17*	FINES	61.4436	26.0771	0.150	AS26*	VRAC	49.3083	16.5935	0.475
PS19*	GERES	48.8451	13.7016	1.132	AS28*	ATD	11.5000	42.8000	0.000
PS21*	THR	35.8200	51.3900	0.000	AS29*	KEG	29.9000	31.8000	0.000
PS23	MKAR	46.8000	82.3000	0.000	AS30*	FURI	8.9030	38.6883	2.545
PS24	KMBO	-1.2740	36.8040	0.000	AS34	MSKU	-1.7000	13.6000	0.000
PS27*	NOA	61.0397	11.2148	0.717	AS36*	IDI	35.3000	24.9000	0.000
PS28*	ARCES	69.5349	25.5058	0.403	AS38	BORG	64.7474	-21.3268	0.110
PS29*	NIL	33.6500	73.2512	0.536	AS43	PSI	2.7000	98.9200	0.000
PS32*	KBZ	43.7286	42.8975	1.023	AS46	KRBA	30.0000	56.8000	0.000
PS33*	ZAL	53.9367	84.7981	0.213	AS47	SHGO	32.1000	48.8000	0.000
PS34*	NRIS	69.0061	87.9964	0.498	AS48*	EIL	29.6699	34.9512	0.210
PS40*	ESDC	39.6755	-3.9617	0.753	AS49*	MRNI	33.0118	35.3920	0.918
PS41	CMAR	18.4575	98.9429	0.307	AS50*	VAE	37.5000	14.4000	0.000
PS42	THA	35.5600	8.7000	0.000	AS56*	ASF	32.2000	36.9000	0.000
PS43*	BRAR	39.7250	33.6390	1.440	AS57*	BRVK	53.0581	70.2828	0.315
PS44*	ABKT	37.9304	58.1189	0.678	AS58*	KURK	50.7000	78.6000	0.000
PS45	AKASG	50.7000	29.2000	0.000	AS59	AKTO	50.4000	58.0000	0.000
					AS60*	AAK	42.6300	74.4800	0.000
					AS61	TAN	-18.9000	47.6000	0.000
					AS62	KOWA	14.5000	-4.0000	0.000
					AS66	MDT	32.8000	-4.6000	0.000
					AS67	TSUM	-19.2022	17.5838	1.240
					AS68	EVN	28.0000	86.8000	0.000
					AS72*	SPITS	78.1777	16.3700	0.323
					AS73	JMI	70.9000	-8.7000	0.000
					AS74	WSAR	23.0000	58.0000	0.000
					AS81*	MLR	45.4917	25.9437	1.360
					AS82	KIRV	58.5850	49.4158	0.000
					AS83*	KVAR	43.9557	42.6952	1.196
					AS84*	OBN	55.1167	36.6000	0.160
					AS85*	ARU	56.4302	58.5625	0.250
					AS94	ZIL	53.9000	57.0000	0.000
					AS96	RAYN	23.6000	45.6000	0.000

Table 1: Recommended Pn and Sn SSSCs for 63 IMS stations

treaty #	station name	lat (N)	lon (E)	elev (km)	treaty #	station name	lat (N)	lon (E)	elev (km)
					AS97	MBO	14.3900	-16.9600	0.000
					AS100	PALK	7.3000	80.7000	0.000
					AS101*	HFS	60.1344	13.6968	0.265
					AS102*	DAVOS	46.8394	9.7943	2.800
					AS103	MBAR	-0.6000	30.7000	0.000
					AS104*	EKA	55.3332	-3.1588	0.353
					AS119	LSZ	-15.2766	28.1882	1.185

treaty #: Treaty number. PS- primary station; AS- auxiliary station. * indicates that there were data from the IMS or surrogate stations in the validation test data sets.

station name, lat, lon, elev: station information for the IMS station used in the SSSCs. The information was taken from the PIDC database when available. Otherwise the information was from the IMS listing (http://g2calibration.cmr.gov/calibration/stalist_ims.html) when available, or from the Treaty.

Table 2: Event relocation tests and data sets

Test Data Sets:				
Data Set	**# of events**	**Purpose**		
Data Set 1	425 Fennoscandian GT events	benchmark with existing 1D SSSCs		
Data Set 2	571 GT0-GT10 events	validation testing of SSSCs in Group-2 region		
Data Set 3	15 GT10 events	extended coverage of region to ocean basins		
Data Set 4	6835 GSETT-3 REB events	real world test using PIDC/IDC data		
Relocation Tests				
Test	**# of events**	**Network**	**Calibrated phases**	**Uncalibrated phases**
Test 2	571 GT0-GT10 events (Data Set 2)	all stations	Pn, Sn	none
Test 3	150 GT5-GT10 events (subset of Data Set 2)	all stations	Pn	none
Test 4	15 GT10 MORT events (Data Set 3)	all stations	Pn, Sn	none
Test 5	6835 GSETT-3 REB events (Data Set 4)	all stations	Pn, Sn	none
Test 6	425 Fennoscandian GT events (Data Set 1)	all stations	Pn, Sn	Pg, Lg, & teleseismic
Test 7	240 GT0-GT10 events (subset of Data Set 2)	IMS only	Pn, Sn	none
Test 8	318 GT0-GT10 events (subset of Data Set 2)	IMS+surrogates	Pn, Sn	none
Test 9	246 &340 GT0-GT10 events (subset of Data Set 2)	IMS only & IMS+surrogates	Pn, Sn	Pn, Sn
Test 10	245 & 328 GT0-GT10 events (subset of Data Set 2)	IMS only & IMS+surrogates	Pn, Sn	Pg, Lg & teleseismic
Test 11	59 & 85 small GT0-GT10 events (subset of Data Set 2)	IMS only & IMS+surrogates	Pn, Sn	Pg, Lg & teleseismic

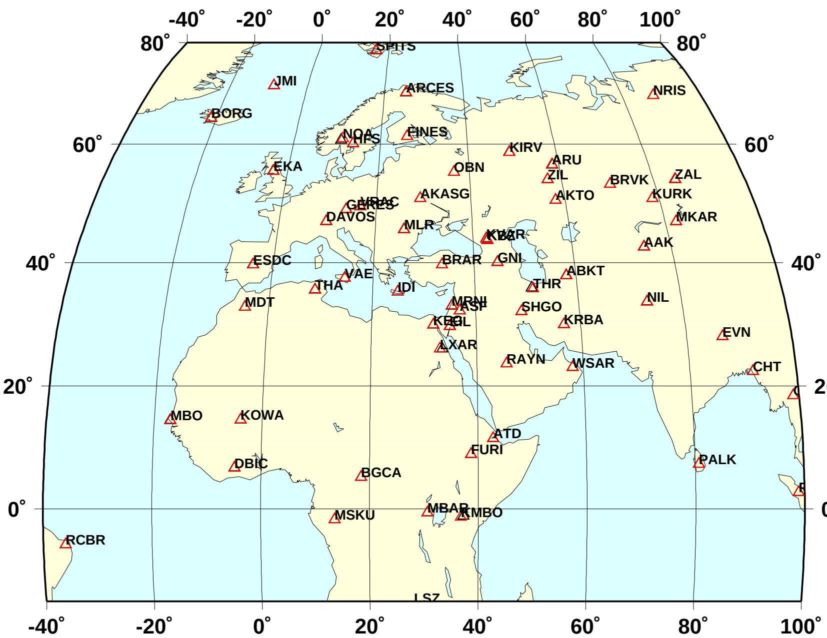


Figure 1.The 63 IMS stations in the Group-2 study region (Table 1). Pn and Sn SSSCs were tested on the CMR Testbed for all 63 IMS stations (Appendix 5).

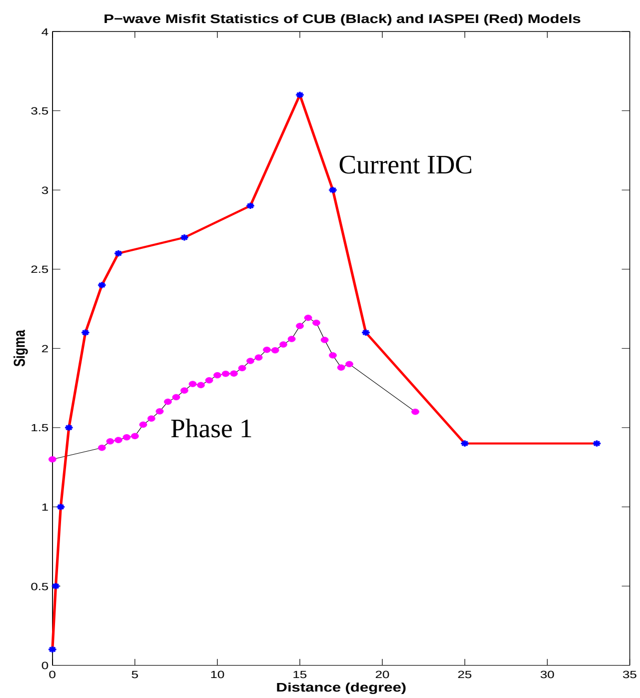


Figure 2. Modeling errors used for Pn SSSCs in Phase 1 (thin line) compared to that used at the PIDC/IDC currently (thick line). They were obtained from travel time misfit of the CUB1.0 Model with respect to IASPEI91 for arrivals in the EHB catalog (Engdahl et al., 1998) (Appendix 4). The modeling errors for Sn SSSCs are doubled from these Pn values.

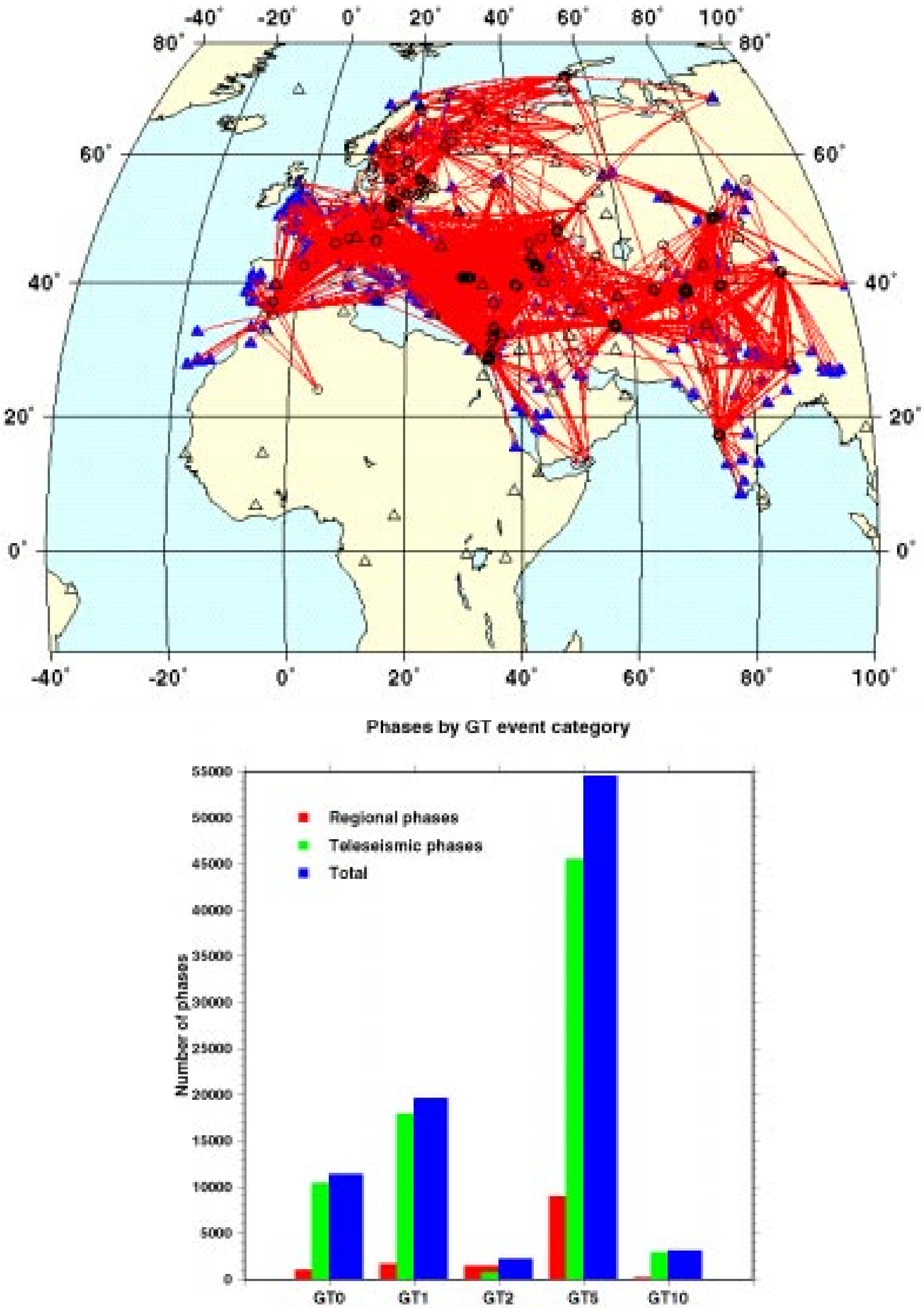
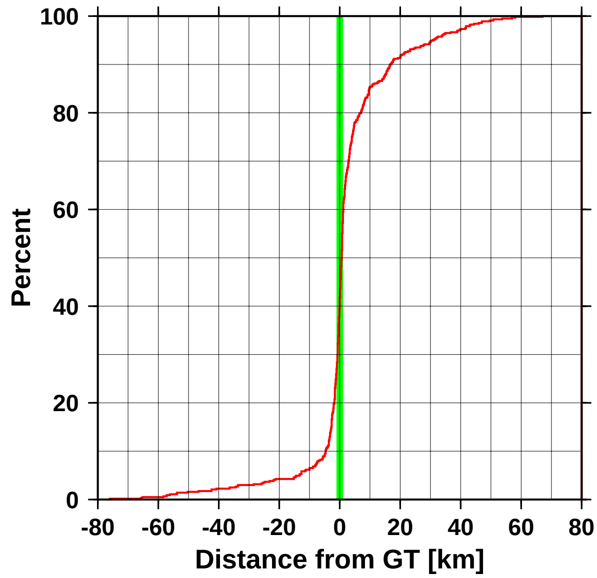
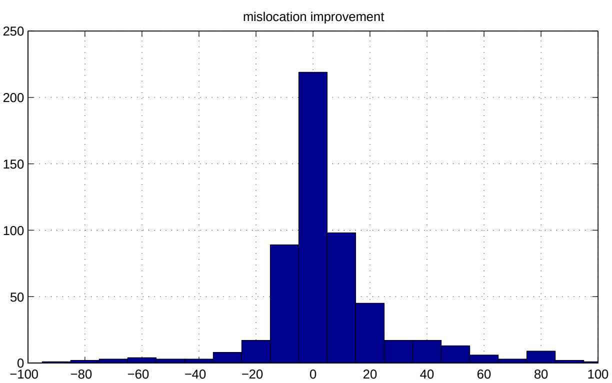


Figure 3. Group-2 GT0-GT10 events used in offline validation testing (Appendices 6-9). There are over 10,000 Pn and 800 Sn path coverage in this test data set. Events (circles) and stations (open triangles for IMS; solid triangles for other stations) are also plotted.





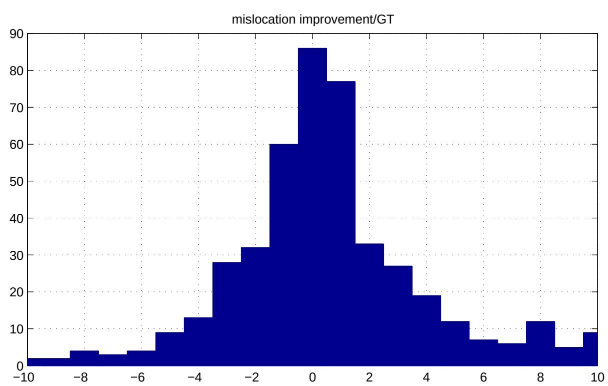


Figure 4. (Top) Mislocation improvement, scaled by GT accuracy, of GT0-GT10 events with SSSCs (Appendix 8). About 31% are uncertain, i.e. within the GT accuracy. About 43% events are improved (40% more events), compared to about 26% events are deteriorated. (Middle and Bottom) Histograms of mislocations improvement with SSSCs. In the bottom plot mislocation is scaled by GT accuracy, assuming GT0 as GT1.

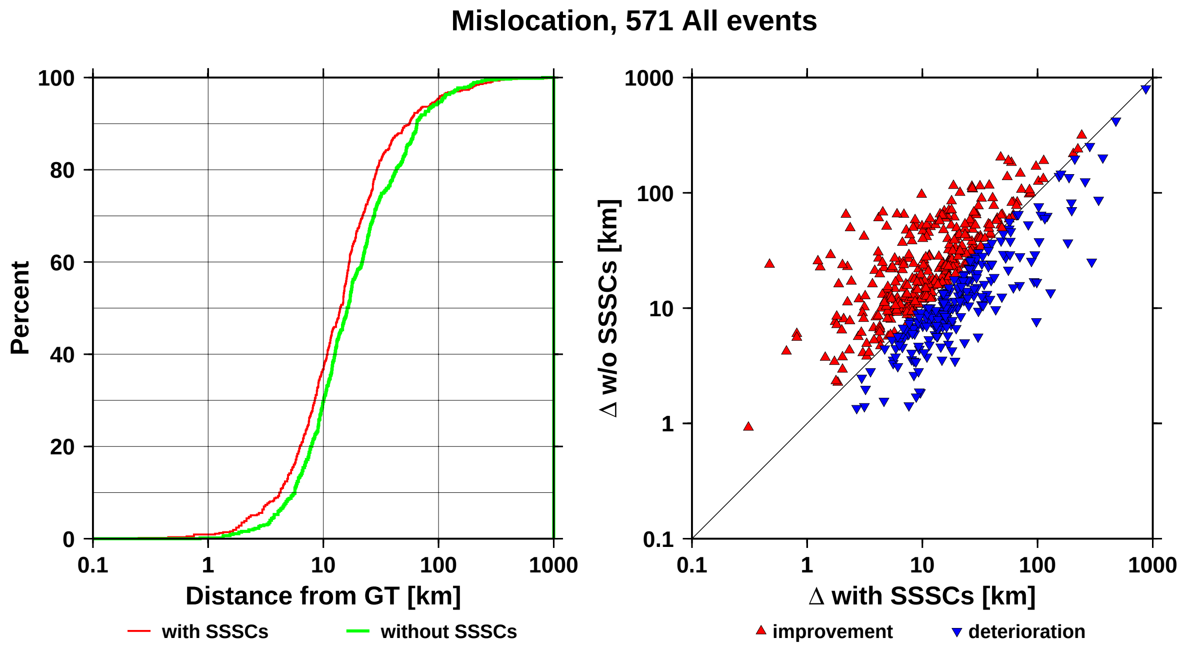


Figure 5. Mislocations of the GT0-GT10 events with and without Pn and Sn SSSCs (Appendix 8). (Left) Cumulative plot of mislocation. (Right) Comparisons of mislocation with and without SSSCs. Symbols above the line indicate improvement with SSSCs.

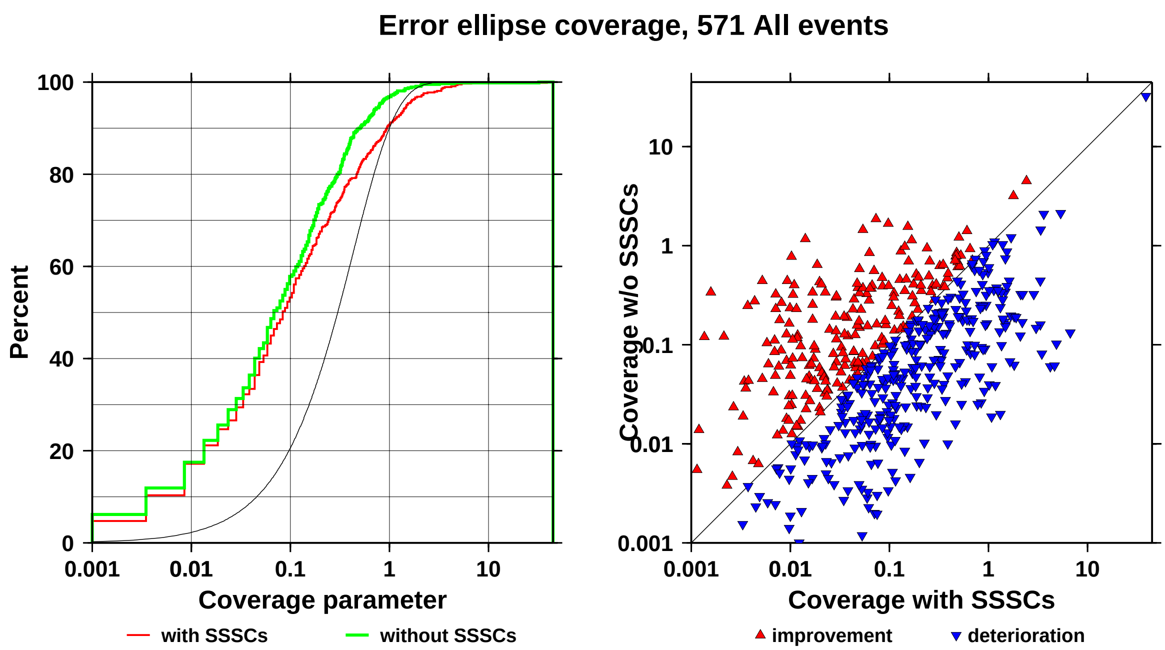


Figure 6. Ellipse coverages of GT0-GT10 events with and without SSSCs (Appendix 8). (Left) Cumulative plot of error ellipse coverage, compared to the χ^2distribution. (Right) Comparisons of ellipse coverage with and without SSSCs. Symbols above the line indicate improvement with SSSCs.

(All Appendices are available at http://g2calibration.cmr.gov/calibration/result.html)

Appendix 1: Model-based Pn and Sn path-dependent travel-time corrections for IMS stations in the Mediterranean, North Africa, Middle East, and Western Eurasia

Summary of Appendice 2-9.

Appendix 2: The CUB model

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Ritzwoller, M., M. Barmin, A. Levshin, A. Villaseñor and R. Engdahl, Pn and Sn tomography across Eurasia, submitted to Tectonophysics, 2001 (http://g2calibration.cmr.gov/calibration/PDF/CUB_TECTO_00.pdf).

Appendix 3: SSSCs from ray tracing

Barmin, M., 2D ray tracer in 3D media and SSSC's construction, Phase 1 document, 2001. (http://g2calibration.cmr.gov/calibration/files/manual.pdf).

McLaughlin, K., SSSC depth dependence, Memo, April 2000. (http://g2calibration.cmr.gov/calibration/files/sssc_memo.pdf)

Appendix 4: Model errors and measurement errors

Bhattacharyya, J., N. Shapiro, M. Ritzwoller, H. Israelsson, X. Yang, and K. McLaughlin, Model error estimation for SSSCs delivered in Phase-1 by the Group-2 Consortium, Phase 1 Delivery Document, 2001 (http://g2calibration.cmr.gov/calibration/files/model_error.pdf; http://g2calibration.cmr.gov/calibration/files/model_error.app.pdf).

Israelsson, H., Measurement Errors from Event Clusters, Phase 1 Delivery Document, 2001 (http://g2calibration.cmr.gov/calibration/files/sdmeas.pdf).

Appendix 5: Online test plan and testing

Yang, X. and K. McLaughlin, Group-2 Patch 1 delivery for Phase 1: GA/ARS testing of SSSCs, Phase 1 Delivery Document, 2001 (http://g2calibration.cmr.gov/calibration/files/patch1.pdf).

Oancea, V. and P. Caron, Phase 1- GA/ARS, Phase 1 Delivery Document, 2001 (http://g2calibration.cmr.gov/calibration/files/test_GA.txt).

Appendix 6: Reference events

Antolik, M., A new joint P and S mantle velocity model and compilation of reference events in oceans, Phase 1 delivery document, 2001 (http://g2calibration.cmr.gov/calibration/files/HRV_Phase1_delivery.pdf).

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Engdahl, R. and E. Bergman, Identification and validation of reference events within the area being regionally monitored by IMS stations in Asia and North America, Proceedings of 23rd CTBT Seismic Research Review, 205-214, Jackson Hole, WY, October 2001 (Phase 1 Delivery Document) (http://g2calibration.cmr.gov/calibration/PDF/srr_engdahl.pdf).

Israelsson, H., Notes from JHD analysis of some event clusters in Europe, Phase 1 Delivery Document, 2000 (http://g2calibration.cmr.gov/calibration/files/gt-jhdmemo.pdf).

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Appendix 7: JHD comparisons

Israelsson, H., J. Bhattacharyya, I. Bondár, K. McLaughlin, and X. Yang, Station path corrections based on event cluster analysis, Phase 1 Delivery Document, 2001 (http://g2calibration.cmr.gov/calibration/PDF/cluster-analysis.pdf).

Appendix 8: Offline validation test

Yang, X., I. Bondár, and K. McLaughlin, Phase 1 validation test report: offline testing of the CUB1.0 model, Phase 1 Delivery Document, 2001 (http://g2calibration.cmr.gov/calibration/files/g2validation.pdf).

Appendix 9: Grid search relocation test

Ritzwoller, M., and A. Levshin, Phase 1 validation test report at CU-Boulder: relocation of ground truth events using regional Pn data based on a 1-D and a 3D model, Phase 1 Delivery Document, 2001 (http://g2calibration.cmr.gov/calibration/PDF/cu_locrpt_phase1.pdf).

Appendix 10: 1999 Oslo Recommendations

Working Group B, Recommendations for seismic event location calibration development, CTBT/WGB/TL-2/18, 1999 (http://g2calibration.cmr.gov/calibration/files/WGB_TL_18.Final.txt).